A petrogenetic study of stromatic migmatites and a model for migmatization at subsolidus conditions

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Diss. Lund. 1985

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Abstract

This thesis considers the formation of stromatic veins in granodioritic metaplutonics in the polymetamorphic gneiss complex of south-western Sweden at Grästorp, Värmlandsnäs and Töcksfors.

A study is performed of the contact pattern between the grains in the leucosomes and paleosomes at Grästorp. An undeformed magmatic granite is used as an independent reference rock. The study is based on photographs of thin-sections from the leuco- and paleosomes. Contacts involving two as well as three grains are studied. The lack of differences in the contact pattern between the leuco- and paleosomes and the existence of differences between the leucosomes and the reference granite indicate a non-anatectic origin for the leucosomes.

The geochemical study comprises analyses of major and trace elements in the leucosomes and paleosomes but also analyses of different mineral phases. The leucosomes at Grästorp and Värmlandsnäs have normative compositions that plot close to the cotectic surfaces *plag. + alk. feldspar + L + V* and *plag. + quartz + L + V*, respectively. The leucosomes at Töcksfors deviate significantly from the cotectic surfaces. Testing the trace element distribution between the leuco- and paleosomes with a non-modal batch-melting model suggests that this model is not applicable for the leucosome formation. There are only insignificant differences in the compositions of the minerals from different parts of the migmatite.

The application of feldspar geothermometry on the Grästorp migmatite yields temperatures $\leq$560°C. A rough estimate with the garnet-biotite geothermometer indicates a minimum temperature of c. 600°C. However, it is very doubtful if these temperatures really reflect the migmatiza-

tion temperature. The results of the geochemical study support metamorphic differentiation as the leucosome forming process.

The metamorphic differentiation model is based on stress-induced diffusional mass transfer due to different mechanical competency of the minerals present. Accordingly, mechanically competent but chemically incompetent high-volume phases like quartz and feldspars stressed in mica-dominated parts of a rock, migrate to parts that are depleted in mica. Hornblende is a common constituent in migmatitic leucosomes. It might be premigmatitic or early synmigmatitic and due to its mechanical competency it initiates and enhances the segregation process. Diffusion takes place along the grain boundaries and is probably enhanced by intergranular fluids. Semi-quantitative estimates of diffusion rates and distances indicate that the model is reasonable and should work over geological times.

A petrogenetic study of stromatic migmatites and a model for migmatization at subsolidus conditions

Introduction

This is an introduction to a Ph. D. thesis comprising the following papers:

1. Karlsson, G. & Wahlgren, C.-H., 1982: A statistical investigation of grain contacts in a migmatite. **Neues Jahrbuch Miner. Mh.**, 248-360.

2. Wahlgren, C.-H., 1984: Discussion of vein genesis in a gneiss complex: an example from south-western Sweden. **Neues Jahrbuch Miner. Abh. 150.**

3. Lindh, A. & Wahlgren, C.-H., 1984: Migmatite formation at subsolidus conditions - an alternative to anatexis. **Journal of Metamorphic Geology 3, 1** (in press). (This thesis.)

Migmatites are very common in metamorphic terrains all over the world. They have been intensely studied since the beginning of the 20th century. Despite this, the question of migmatite formation is still controversial. Mehnert (1971) compiled the migmatite literature in a book which ever since has been regarded as a standard work. The two processes most often advocated for migmatite formation are anatexis and metamorphic differentiation. The major problem is thus to decide whether the veins are the product of partial melting or of diffusion in the solid state. There is a lot of melting experiments performed on granitic rocks (cf. Wyllie 1977). However, it is much more difficult

to experimentally simulate a metamorphic segregation process. This is possibly one of the reasons why the anatectic model is mostly favoured.

The present study was carried out in order to investigate the genesis of stromatic veins in granodioritic metaplutonics, examplified with rocks from the gneiss complex of south-western Sweden.

The genesis of migmatites is commonly deduced from chemical investigations of the different components of the rock, i.e. the leucosome, melanosome and paleosome (mesosome). This approach usually comprises (1) chemical analyses of major and trace elements and (2) chemical analyses of different mineral phases. In an effort to expand the petrogenetic study, a statistical analysis of the contact pattern between the grains in the leucosomes and paleosomes was performed on one of the migmatites. Earlier only a very small number of quantitative studies of contact patterns are reported. However, recently McLellan (1983) reported results from a similar study of migmatites from the Scottish Caledonides. The method applied in the present study has not been used before. Thus, the study is designed as a "pilot-study". These circumstances introduced some uncertainties in the interpretation of the obtained results. However, if the leucosomes are formed by partial melting some differences in the contact pattern should be expected between the leuco- and paleosome. As an independent reference rock an undeformed, unmetamorphosed and clearly magmatic granite was used.

The geochemical study comprises among other things a comparison of the leucosome compositions with experimental data from studies of incipient melting; i.e. do the leucosomes have a minimum melt composition? Furthermore, the trace element distribution between the leuco- and paleosome is compared. A theoretical batch melting model is tested

in order to compare the observed trace element distribution with the one expected in a batch melting process.

Under equilibrium conditions, the plagioclase component of the melt is expected to be more albitic than the plagioclase in the associated unmelted fraction. Other mineral phases forming solid solution series, such as biotite and hornblende should show similar differences; i.e. they should not have the same composition in all parts of a migmatite formed by partial melting. A test of this hypothesis reveals that the mineral compositions in the leuco-, melano- and paleosomes are very similar.

An attempt was made to estimate the migmatization temperature for one of the migmatites by using the two-feldspar geothermometer.

In the last paper a model for migmatization at subsolidus conditions is presented. It is based on stress-induced diffusional mass-transfer as a result of different mechanical competency of the occurring minerals. For example, quartz and feldspar stressed in mica-dominated parts of the rock (high mean pressure, $\bar{\sigma}$) will migrate to quartz and feldspar dominated parts of the rock (low $\bar{\sigma}$). Consequently, diffusion takes place down a mean pressure gradient created in the rock due to differences in mechanical competency.

The results are reported in the following papers:

1. A statistical investigation of grain contacts in a migmatite.
In the first report a new method is used to study and compare the contact pattern among grains in the leuco- and paleosomes in a migmatite at Grästorp, south of Lake Vänern, south central Sweden. The contact pattern was also compared with that in a magmatic granite.

The study is based on photographs of thin-sections, where every mineral phase has been marked and given an identity number. Contacts involving two as well as three grains are studied. The ratio

observed number of contacts/expected number of contacts

is evaluated for each photograph and each type of contact (quartz/-quartz, microcline/microcline etc.). No significant difference in the contact pattern could be established between the leuco- and paleosomes. In order to see if aggregates of small grains possibly represented disintegrated large primary grains, one of the photographs from a leucosome was modified by letting the aggregates of like small grains coalesce to larger grains. This modification did not significantly change the contact pattern nor the conclusion of no difference in the contact pattern between the leuco- and paleosomes. However, differences were discovered between the contact pattern in the leucosomes and in the reference granite. The obtained results are consistent with the suggestion that the leucosomes are formed by metamorphic differentiation. A development of the study of grain contacts may in the future be of great value to decide the origin of crystalline rocks.

2. Discussion of vein genesis in a gneiss complex: an example from south-western Sweden.

In the second paper, the genesis of the veins in the Grästorp migmatite but also in migmatites at Värmlandsnäs and Töcksfors in south-western Värmland, south central Sweden, is investigated chemically. The leucosomes at Grästorp and Värmlandsnäs are granitic in composition while the leucosomes at Töcksfors are granodioritic to tonalitic. In the

neosomes at Töcksfors and Grästorp hornblende occurs as a reaction product from the breakdown of biotite.

The leucosomes at Grästorp and Värmlandsnäs have normative compositions that plot close to the cotectic surfaces separating the plagioclase - alkali feldspar and plagioclase - quartz spaces respectively in the Qz-Ab-Or-An tetrahedron (Winkler et al. 1975, 1977). The normative compositions of the leucosomes at Töcksfors deviate significantly from the cotectic surfaces, and neither do they follow a possible melting path of the paleosome.

The trace element distribution between the leuco- and paleosomes is difficult to interpret. However, the results of a test of the nonmodal batch melting model on the studied migmatites suggest that this model is not applicable for the formation of the leucosomes. This can be said with certainty for the migmatite at Töcksfors but it is probably also true for the migmatites at Grästorp and Värmlandsnäs.

If the migmatites are formed by partial melting, the plagioclase in the leucosomes should, at equilibrium conditions, be more albitic than the plagioclase in the paleosomes. However, the differences in plagioclase compositions within the three migmatites are insignificant. Neither are there any significant differences in the composition of the biotite and hornblende. This, together with higher K/Rb and Ba/Rb and lower Rb/Sr and K/Ba ratios for the leucosomes compared to the paleosomes suggest that the migmatization constitutes a more or less isochemical process without major external contributions.

Estimates of the migmatization temperature are uncertain due to the total lack of metamorphic index minerals. An attempt to use the two-feldspar geothermometer on the Grästorp migmatite was made. Temperatures $\leq$560°C were obtained. However, these temperatures most likely represent the blocking temperature for alkali diffusion between the

coexisting feldspars. A rough estimate with the garnet-biotite geothermometer indicates a minimum temperature of c. 600°C for the Grästorp migmatite.

The results of this study support metamorphic differentiation as the migmatization process, especially for the Töcksfors migmatite but probably also for the migmatites at Grästorp and Värmlandsnäs.

3. Migmatite formation at subsolidus conditions - an alternative to anatexis.

Partial melting is the segregation mechanism most often advocated for migmatite formation. However, many features are not in accordance with such an origin and/or may be explained in an alternative way. In this third paper possible principles for migmatization at subsolidus conditions are hypothesized. The hypothesis develops a suggestion by Robin (1979) and offers a new approach to the migmatite problem. It is developed here as a theoretical model to initiate discussion. Support for the model comes principally from literature data, but much more, especially experimental data are required to refine it.

Leucosomes are made up of quartz and feldspars and often approximate a minimum melt composition. This last observation is usually put forward as a strong indication for an anatectic origin of the leucosomes. However, quartz and feldspars are also high-volume (low-density) phases which assemble at low-pressure parts in the rock. The mesosome in migmatites shows evidence of deformation, i.e. a gneissic fabric. The mineral composition and the generally coarser grain-size make the leucosomes the mechanically competent part of the rock. It is assumed that differences in strain between the meso- and leucosomes are not necessarily a result of a later deformation but may be an integral part of the formation history.

Augengneisses are an often observed constituent in metamorphic terrains. Occasionally, a gradational transition from a megablast to a migmatitic vein is observed. This implies a close genetic link between augen and vein formation.

The possible amount of water in the protolith of a migmatite can be estimated from grain boundary widths, the amount of fluid inclusions and water liberated in syn-migmatitic dehydration reactions. The estimated maximum water content is not sufficient to saturate enough melt to allow crystallization of 20-30 % leucosome material.

Segregation of 'neosomes' at low and medium grades (<550°C) is often observed. As examples, banded mylonites, flecky gneisses, pressure shadows and layering discordant to bedding, may be mentioned. This implies that diffusion works at low temperatures. At higher temperatures diffusion rates increase according to an Ahrenius equation. Thus, diffusion must be an important segregation mechanism even if temperature and water content allow partial melting.

The solid state model is based on the supposition that the diffusion of a component occurs in response to gradients in mean pressure, $\bar{\sigma} = \frac{1}{3} \sum_{i=1}^{3} \sigma_i$. This model presumes the presence of grains with different mechanical competency. The essence of the model is that mechanically competent phases such as quartz and feldspars stressed in mica-dominated parts of a rock (high $\bar{\sigma}$) migrate to parts of the rock that are depleted in micas (low $\bar{\sigma}$). Thus, the mechanically more competent parts begin to grow parallel to σ_3 creating pressure shadows. Segregations into these pressure shadows will enlarge the mechanically competent parts, rendering them even more effective traps for chemically

incompetent but mechanically competent species. Diffusion through the lattice is very slow at ordinary temperatures. Even diffusion along dry grain boundaries might be insufficient to explain the formation of segregations. However, the presence of water in the grain boundaries enhances the diffusivity, and makes it compatible with the diffusivity required if diffusive segregation would work in the low pressure gradients met with in natural rocks.

Hornblende sometimes occurs in migmatitic leucosomes as a reaction product of biotite decomposition. It is suggested here that the hornblende may be premigmatitic or early synmigmatitic and initiates and enhances the segregation process.

A semi-quantitative estimate of the resulting flux in a diffusional process, using experimentally determined and tabulated diffusion coefficients and assuming the mean pressure to decrease linearly with distance, gives for grain boundary diffusion a minimum time of 10^6 years for the formation of a 8 cm wide leucosome. For lattice diffusion the time needed would, however, be an improbable 10^{12} years.

The preservation of zoning in some minerals testifies to the minor importance of lattice diffusion in comparison to grain boundary diffusion as already pointed out.

If leucosomes show evidence of deformation, this is usually interpreted to be due to a later deformation event. However, it is suggested that this could also be explained by a synsegregational dynamic recrystallization caused by a non-hydrostatic pressure.

Acknowledgements

I am very grateful to all who have helped and supported me during the completion of this thesis. Especially, I want to express my sincere gratitude to Dr. Anders Lindh for his inspiration, for many interesting discussions and for improving all the papers in the thesis. I am also indebted to Professor Roland Gorbatschev for discussions and valuable criticism on the papers. Erna Hansson is thanked for typing, Dr. Zoltan Solyom and Ingrid Johansson for their analytical work, Josef Gersner for making the thin-sections, Christine Ebner for some of the drafting work and the rest of the staff at the Institute of Geology together with all friends and colleagues for help and support.

I want to thank Professor Ove Frank and Dr. Sven Berg at the Department of Statistics, University of Lund, for criticism on the first paper, Professor Christopher Talbot, Institute of Geology, University of Uppsala, for interesting discussions and valuable criticism on the third paper and Professor Wilhelm Johannes, Institut für Kristallographie und Petrologie der Universität, Hannover, Federal Republic of Germany, and my colleagues at the Geological Survey of Sweden, Uppsala, for criticism on the last two papers. The technical staff at the Geological Survey is also thanked for some help and assistance. The mineral analyses were performed at the Department of Mineralogy and Petrology, University of Cambridge, Great Britain. I am very much indebted to Drs. Jim Long and Peter Treloar for invaluable help and assistance.

Financial support have been obtained from the Swedish Natural Science Research Council (NFR), the Swedish Council for Research in the Humanities and Social Sciences (HSFR), Th. Nordströms Fond, Kungliga Vetenskapsakademien and Landshövding Per Westlings minnesfond.

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Migmatite formation at subsolidus conditions - an alternative to anatexis

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Migmatite formation at subsolidus conditions - an alternative to anatexis

ABSTRACT

This contribution discusses formation of stromatic high-grade migmatites. Volume considerations require that most of the leucosome material is not added from outside the system. A segregation mechanism is necessary except in those cases, where the protolith of the migmatite already had a banded structure. Although partial melting is most often advocated to provide the segregation mechanism, several arguments can be raised against high degrees of melting: Mineral compositions and even zoning patterns are similar in both meso- and leucosomes, sufficient degrees of melting at reasonable temperatures require more than available amounts of water, the leucosomes do not always approximate a minimum melt composition, high degrees of melting cannot occur without an appreciable volume increase etc. Diffusion works as a segregation mechanism at low temperatures. As diffusion rates increase exponentially with temperature it must become still more important as a segregation mechanism at high temperatures. A model is suggested based on diffusion of components in response to the gradient $\partial\bar{\sigma}/\delta x$, where $\bar{\sigma} = \frac{1}{3}\sum_{i=1}^{3} \sigma_i$ is the mean pressure. In homogeneously strained rocks, σ_3 is larger in rock parts rich in than in rock parts depleted in incompetent phases. Accordingly mechanically competent but chemically incompetent high-volume phases like quartz and feldspars stressed in mica-dominated parts of a rock (high $\bar{\sigma}$) migrate to parts of the rock that are depleted in mica (low $\bar{\sigma}$). It is suggested that hornblende occurring in many leucosomes may be premigmatitic or early synmigmatitic and due to its mechanical competency it initiates the segregation. Diffusion occurs along grain boundaries

and is enhanced by small amounts of "intergranular fluids". At the best, semi-quantitative estimates of diffusion rates and distances indicate that the process should work over geological times.

Keywords: stromatic migmatite; diffusion; stress-gradient; segregation; water content.

INTRODUCTION

Migmatite means "mixed rock" and it is composed of a light leucosome, usually a dark adjoining melanosome and an intermediate mesosome component. In many interpretations the mesosome corresponds to the paleosome, which is supposed to have been essentially unaffected by migmatization. Migmatites can form in many environments and may be quite different in appearance. In order to delimit the subject, our discussion will be mainly restricted to stromatic migmatites found in high-grade metamorphic terrains.

Although migmatites and veined gneisses are widespread in metamorphic terrains, their origin is still controversial. Attempts to present universally valid models for their formation have not been successful. Most authors advocate a segregation mechanism based on partial melting. This model is founded on melting experiments. A metamorphic segregation model based on diffusion in subsolidus conditions is much more difficult to simulate experimentally.

According to our experience partial melting cannot be considered as a general mechanism for formation of stromatic migmatites. Consequently, we want to discuss possible principles and ideas concerning migmatite formation. However, it should be pointed out that we do not deny the existence of anatectic migmatites.

We first outline common field relations and chemical characteristics of migmatites. We then continue to discuss and point out shortcomings in models for migmatite formation based on partial melting. Finally, we discuss principles for a model based on subsolidus diffusion.

SOME BASIC FACTS

Migmatites can be formed from any parent rock; e.g. the migmatites discussed by Karlsson and Wahlgren (1982) and Wahlgren (1984) are formed from plutonic rocks. The protoliths may be homogeneous or they may be inhomogeneous (cf. Johannes & Gupta 1982, Gupta & Johannes 1982). In plutonic and high- and medium-grade metamorphic rocks water is found in hydrated minerals, fluid inclusions and possibly along the grain boundaries. No migmatites known to us appear to have been appreciably affected by hydrothermal alteration except some sericitization of feldspars. These circumstances do not suggest vast amounts of water participating in a migmatite forming process. The mesosome in stromatic migmatites usually exhibits a gneissic fabric. The veins are normally concordant to this fabric even if slightly discordant veins may occur. Although, the original relations between leucosome orientation and gneissosity are seldom clear, stromatic migmatites showing no folding are usually believed to have formed normal to σ_1 (maximum compressive stress), and not to have been rotated into this position.

The leucosomes are made up of quartz and feldspars and often approximate a minimum melt composition. However, these minerals are also high-volume phases and will consequently be assembled at low pressure areas in a stressed rock. The mineral composition and a normally coarser grain-size make the leucosome the most mechanically competent part of the

rock. We assume that the commonly observed difference in strain between meso- and leucosomes may be an integral part of the formation history.

White (1966) and Olsen (1982) reported that the mesosome adjacent to the melanosome was impoverished in potash feldspar. The impoverished zone was a couple of centimetres in width. If specifically looked for, this feature might be more common than assumed.

Mineral compositions, especially of plagioclase, have been shown to be similar in all parts in many migmatites (e.g. Kretz 1966, Misch 1968, Mehnert 1971, Hedge 1972, Ashworth 1976, Yardley 1978, Henkes & Johannes 1981, Gupta & Johannes 1982, Johannes & Gupta 1982, Wahlgren 1984). Even the zoning pattern in the plagioclases is sometimes similar (e.g. Wahlgren 1984). However, Misch (1968) found that in the migmatites investigated by him, plagioclase in leucosomes are more albitic and also more homogeneous than in the corresponding rocks in non-migmatized terrains.

Trace element distributions between the meso- and leucosomes are difficult to interpret. For example, K/Rb ratios are usually higher in the leucosome than in the corresponding mesosome (White 1966, Whitney 1969, Mehnert & Büsch 1982, Wahlgren 1984), whereas K/Ba ratios show the inverse relationship (White 1966, Wahlgren 1984).

Migmatites are usually found in metamorphic terrains of middle to upper amphibolite facies. Thus, in auspicious conditions they may enter the realm of incipient melting. The peak temperature may have been higher but the mineral parageneses normally fail to indicate this. Reasonable temperatures for migmatite formation are thus 575-675°C.

Repeated migmatization events

Many migmatites contain more than one generation of veins. If a migmatite formed by partial melting is exposed to a later anatectic event, the earlier formed veins should, due to their approximate minimum melt composition, be remobilized and reorientated in the new stress field before the mesosome is appreciably affected. Touret & Dietvorst (1983) observed that in an amphibolite, fluid inclusions were far more abundant in the mobilizates than in the mesosome. If this difference persists until the next migmatization event and if equal amounts of fluids are assumed

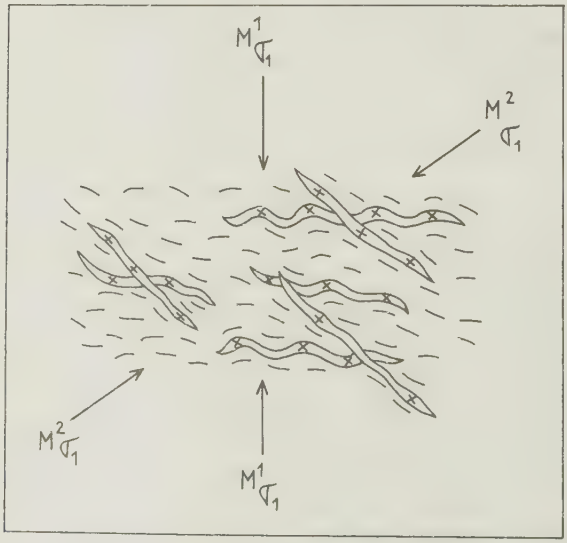


Fig. 1. A principle sketch of discordant veins belonging to different migmatization events. M^1 = first migmatization, M^2 = second migmatization, σ_1 = maximum compressive stress.

along the grain boundaries in the mesosome and the veins, and further that no water is liberated by dehydration reactions, more fluid is likely to be present in the already existing mobilizates than in the mesosome. Nevertheless, the second generation of veins is often discordant to the earlier veins (Fig. 1). This implies that the mesosome has been mobilized, and that the earlier veins may have recrystallized but otherwise are essentially unaffected. A possible explanation might be that both or at least one of the leucosome generations are metamorphic differentiates.

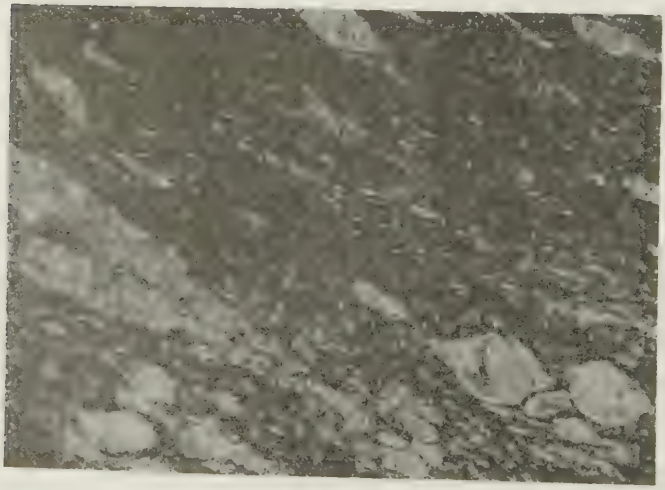
The relation augens - veins

Augen gneisses are an often observed constituent in migmatitic terrains. A common phenomenon is a gradational transition from an augen (megablast) to a migmatitic vein. All transitional stages between perfectly rounded augens and normal veins can sometimes be seen in the same outcrop (Fig. 2). This observation implies that sometimes a close genetic link exists between augen and vein formation. As a general rule, well-preserved transitional stages from an "embryonic" to a normal vein appear to be less commonly observed, or if observed usually misinterpreted. This does of course not imply that all veins necessarily constitute enlarged and elongated augens.

SEGREGATION

One working model for migmatite formation suggests differential melting of initially heterogeneous rocks to form migmatites (Johannes & Gupta 1982, Gupta & Johannes 1982). This model explains where the neosomes

a



b

Fig. 2. Photographs showing the relation between augen and veins. (a) Augen and elongated augen. (b) Augen and veins.

form and partly circumvents the major segregation problem. *Migmatites may, however, form in all types of rocks including homogeneous plutonics.* Thus, a model that presupposes major heterogeneities in the protolith cannot be the most general one.

Another alternative to segregation is injection of silicate melts from outside the system producing arterites. However, addition of all the leucosome material (10-30 % of the rock) from outside results in a volume increase of many tens of km^3. On a regional scale such migmatites must reasonably be of minor importance.

There are two main models for segregations:

i Partial melting, migration of melt along grain boundaries and accumulation into leucosomes.

ii Diffusion in the solid state possibly enhanced by an intergranular fluid.

PARTIAL MELTING

Most segregation models are based on partial melting. Supporting evidence is found in many experimental investigations since most leucosomes approximate a minimum melt composition. However, this does not confirm an anatectic origin of the leucosomes so long as there are no comparable results from experiments on metamorphic differentiation. Melting requires a fluid phase, usually water, to depress the melting temperature. If the leucosomes had crystallized from saturated melts the protolith to a migmatite with 20-30 % leucosome material requires approximately 2-3 weight percent water (i.e. the double in volume percent) as a free phase. Experiments on granitic liquids indicate that natural magmas

contain less than 1.5 wt % water if the order of crystallization is consistent with petrographic evidence (Maaløe & Wyllie 1975). Some, perhaps most, of this water is expelled during crystallization, the rest is found in hydrated minerals, liquid inclusions and as an intergranular fluid. Fluid inclusions normally constitute much less than 1 volume % of a rock. Grain boundary volumes can be estimated from grain sizes and grain boundary widths. Assuming a mean grain diameter of 3 mm and a boundary width of 200 Å, the grain boundary volume is of the magnitude 10^{-3}%. A grain boundary width of 200 Å is larger than expected. Free water in amounts exceeding 0.5 wt % would thus not be expected in a normal rock; breakdown of biotite adds another 0.5 wt %. However, melting experiments on biotite bearing rocks under dry conditions require temperatures over 700°C for incipient melting to occur (Brown & Fyfe 1970, Thompson 1982). Water can of course be added to a rock as witnessed by retrograde alterations. Applying the model described by Johannes & Gupta (1982) and Gupta & Johannes (1982), where the melt is more or less stationary, requires less amounts of water (<1 wt %, Johannes 1984).

The temperature at which migmatite formation takes place is difficult to quantify. The mineral composition of the leucosomes does not allow any accurate temperature estimates. However, it is logical to assume that the mineral parageneses in the mesosome reflect the migmatization temperature. Another approach would be to use oxygen isotope distributions between coexisting minerals for temperature determinations (cf. Henkes & Johannes 1981). Consequently, an acceptance of today's sparse knowledge of water content and migmatization temperatures does not suggest partial melting as the most general model. However, if evidence

could be presented that migmatites generally form at higher temperatures than assumed here, it becomes easier to accept partial melting as a general segregation mechanism.

Leucosomes formed by accumulation of melt portions should have a minimum melt composition. Allowing for the uncertainties in cotectic compositions of natural magmas, most leucosomes approximate this condition; indeed, the normal minimum melt composition is the strongest evidence for a partial melting origin. However, there are exceptions. For example Wahlgren (1984) describes a migmatite, where the leucosomes should begin to melt at a higher temperature than its associated paleosome (mesosome).

Since most minerals are members of solid solution series, an equilibrium melting process should give rise to different compositions of the minerals in the solid residue and in the rock portion crystallized from the newly formed melt. This is not always the case for plagioclase, and Wahlgren (1984) reports the same inconsistencies for biotite and hornblende (see also Kretz 1966). Johannes (1978, 1980) accounts for the similarity of plagioclase composition in the neosome and mesosome using a nonequilibrium melting model; an obvious alternative is that no melts were involved in the process.

If the leucosomes crystallized from a melt, allowance must be made for a volume increase of the melted rock portion. If the volume increase on melting is about 5 % and the migmatite has 20-30 % leucosome material, a total volume increase of 1-1.5 % would result. Furthermore, if c. 20-30 % of many km^3 of migmatitic rocks really were partially molten, the density and viscosity of the whole rock volume would be reduced. This should result in an upwelling of the migmatite to a level where

gravitational equilibrium is reached. Migmatitic upwelling has been described from e.g. Greenland (Talbot 1979), but does not seem to be very often observed. However, in polymetamorphic terrains later deformation and metamorphic events may erase the evidence for any such upwelling ("intrusion").

Another critical point is the orientation of the leucosomes in relation to the then prevailing stress field. Because of the wellknown tendency of fluid fractions to form layers perpendicular to the most tensile stress (e.g. Savage 1969), leucosomes should be orientated parallel to the σ_1-σ_2 plane. However, Yoder (1976) pointed out that in the presence of a fluid phase, melt fractions *might* be orientated with their long axes parallel to σ_3 similar to a leucosome formed in the solid state. Hence, the orientation of the leucosomes in relation to the gneissic fabric may not help us to discriminate between partial melting and metamorphic differentiation, unless there is some information on the fluid pressure. Leucosomes cutting the foliation might after crystallization be folded and rotated into parallelism with σ_3.

DIFFUSIONAL SEGREGATIONS AT LOW TEMPERATURES

Before discussing the diffusion mechanisms at high metamorphic grades, it is convenient to consider briefly the segregation of neosome at low and medium grades where no melting can occur (<550°C). Banded mylonites may form from more or less homogeneous rocks. They are certainly not low temperature analogues of migmatites since they form as a degradation process, but nevertheless they imply that diffusion can work at low temperatures. Formation of flecky gneisses (Loberg 1963), crystallization of 'neosome' in pressure shadows around pyrites and garnets or between

boudins are all wellknown features formed at temperatures well below the solidus. Segregations of 'neosome' discordant to bedding in low grade rocks have also been described (e.g. Talbot & Hobbs 1968). Petrographically many of these low-temperature segregations resemble the felsic component of a migmatite, although they are generally accepted to have formed in subsolidus conditions. It is also worth mentioning that e.g. Mehnert (1971) and Vidale (1974) found that rocks of low to medium metamorphic grades show quartz-albite-rich mobilizates; i.e. mobilizates that do not approximate a minimum melt composition form in low temperature environments. At higher temperatures diffusional processes increase in velocity, since diffusion follows an Ahrenius equation. Consequently, diffusion must be important as a segregation mechanism even if temperatures and water availability allow partial melting.

Nicolas & Poirier (1976) pointed out that during stress-induced diffusion processes, atoms are transported from grain boundaries suffering compression to boundaries suffering tension, through the crystal lattice (Nabarro-Herring creep) and/or along the grain boundaries (Coble creep). Such a process offers a model for a stress-induced segregation process in a metamorphic rock, even if the necessary diffusional distances exceed those of a single crystal by many times (c. 100 millimetres instead of 1 millimetre).

SOLID STATE DIFFUSION AS AN ALTERNATIVE TO PARTIAL MELTING

The points put forward above call for a process for migmatite formation that is an alternative to partial melting. Such a process could be based on diffusional transfer through rocks. Two different diffusion paths

are possible, along the grain boundaries or through the lattice. Fisher (1977) considered grain boundary diffusion to be the all-dominant rate-controlling process for geological structures in all but aphanitic rocks.

Diffusion in solid rocks is still one of the least understood geological processes. Hence, tests of proposed models are difficult to perform rigorously. At low temperatures we can only expect enrichments of the most mobile ions. This is in agreement with observations that mobilizates in low-grade rocks are quartz and albite rich but microcline poor. It is also consistent with lower K/Rb ratios in the mesosome than in the leucosome in high grade migmatites, but not with observed K/Ba ratios. Trace element contents are, however, governed not only by diffusion rates. Biotite in the mesosome is e.g. expected to concentrate Rb more than microcline in the leucosome, while Ba prefers microcline in the leucosome to biotite in the melano- and mesosome. It is thus not clear which mechanism bears the prime responsibility for the observed distributions.

The separation distances between adjacent leucosomes differ in most natural migmatites. If the migmatites are formed by diffusional segregation, the melanosome and the potash feldspar depleted zone (< 3 cm) between the melanosome and the "normal" mesosome can be used to estimate minimal diffusion distances. These are thus about 3 cm + the half width (2-7 cm) of the leucosome i.e. 5 to 10 cm. Maximum diffusion distances would be half the separation distance between the leucosomes i.e. 0.5 to 1 m.

It is difficult to quantify time involved in a migmatization process. It is a deep-seated process where heat only escapes slowly and it is

associated with regional metamorphism. Consequently, the processes probably take place over a rather long period of time which could last up to 10 million years.

THE MODEL

Robin (1979) sketched a model that can be elaborated somewhat. His proposals go back to a suggestion by Ramberg (1949), who introduced the concept of chemical squeezing. Diffusion of a component would occur in response to gradients in the mean pressure $\bar{\sigma} = \frac{1}{3} \sum_{i=1}^{3} \sigma_i$. Robin's model assumes the presence of grains with different strain rate/stress relationships. If the same strain rate is imposed throughout the rock, those parts richer in easily strained grains require a lower differential stress $\sigma_1 - \sigma_3$ to yield. Mechanical equilibrium requires that σ_1 has the same value in all the grains (rock parts). If all grains expand parallel to σ_3 at the same rate than the mean pressure is higher in the mechanically incompetent parts. This type of stress/strain distribution has been demonstrated experimentally in a simulation of boudin structures (Strömgård 1973).

The starting configuration of the model is a random distribution of mechanically competent points in the rock, be it hornblende (Fig. 3), larger grains, or a local depletion of mechanically incompetent phases such as micas. The essence of Robin's model is that mechanically competent phases such as feldspars and quartz stressed in mica-dominated parts of a rock (high $\bar{\sigma}$) migrate to parts of the rock that are depleted in micas (low $\bar{\sigma}$). Thus, in an applied stress field heterogeneities that are initially mechanically more competent begin to grow parallel to

σ_3. The crucial point in the model is the difference in strain rate of different parts of a rock when exposed to the same differential stress. To the best of our knowledge, experiments designed to simulate this behaviour do not exist.

Segregation in pressure shadows will enlarge the mechanically competent parts rendering them even more effective traps for the chemically incompetent but mechanically competent species. A self-perpetuating situation has been created. An increasing amount of mica in the melanosomes enhances the process due to an increasing difference in $\bar{\sigma}$. A wide biotite seam will, however, impede diffusion velocities across the seam. On very vague evidence Robin (1979) suggested that when the mica/mica+quartz ratio is higher than about 2/3, the mechanical competence increases with increasing mica content. This is consistent with our experience that mica-rich rocks generally have thinner leucosomes (a few centimetres) than rocks with moderate mica contents (10-15 %) that might have leucosomes up to 8-10 cm in width. Ortoleva et al. (1982) presented a theory for a spontaneous development of differentiated layering in an initially unbanded rock, where the driving force is an anisotropic stress. The segregation develops through a combination of reactions and grain boundary diffusion. A stromatic migmatite may be considered as a differentially layered rock.

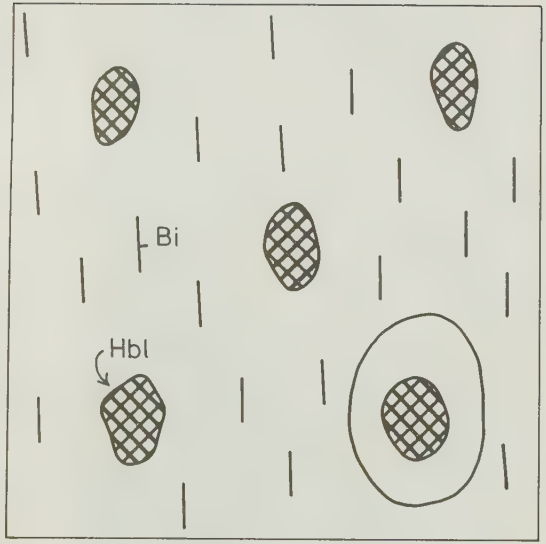
The role of hornblende

Scattered grains of hornblende are common in the leucosomes of many migmatites (Fig. 3). This occurrence can be explained in two different ways. Usually, the hornblende is considered to have formed during the migmatization by the breakdown of biotite, whether by anatexis or meta-

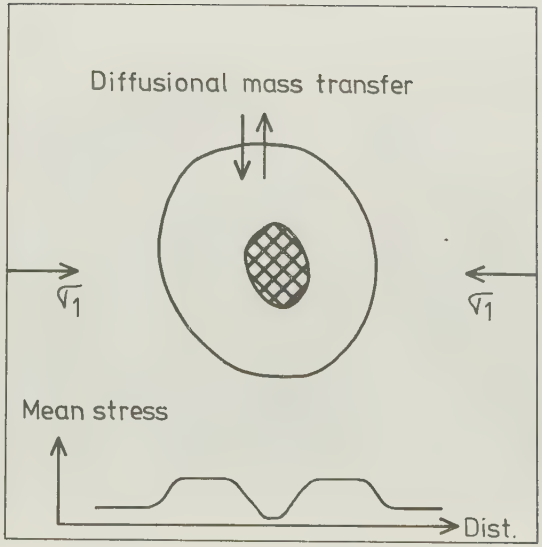
a

b

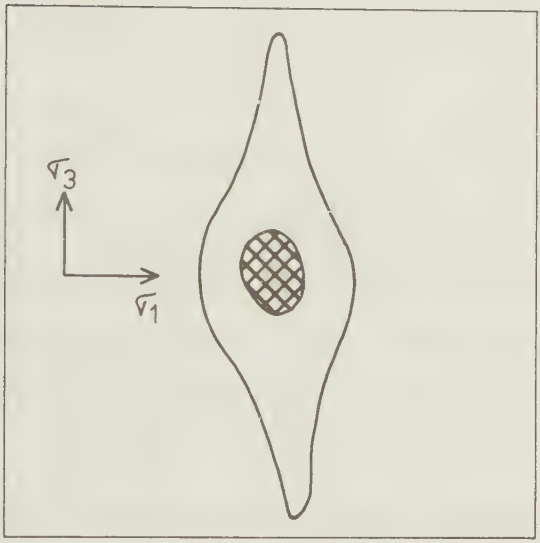
Fig. 3. Scattered hornblende grains (black dots) in stromatic leucosomes (a-b). The hornblende is mainly concentrated in the leucosomes, only sparse grains occur in the mesosomes.



a



b



c

Fig. 4. Conceivable development of a migmatitic vein (a-c), initiated by the formation of hornblende by prograde breakdown of biotite.

morphic differentiation. Alternatively, the hornblende originally formed as porphyroblasts in the unmigmatized rock by prograde breakdown of biotite at subsolidus temperatures, due to e.g. low a_{H_2O}. Inclusions of biotite testify to their origin.

Hornblende is more mechanically competent than biotite. Consequently, the hornblende grains are themselves mechanically competent phases sitting in rock parts devoid of incompetent phases. Thus, the heterogeneous stress pattern required by Robin's model is formed. This discussion does not mean that hornblende porphyroblasts are a requisite for Robin's model to work; it is one of many ways to create an inhomogeneous stress pattern. This line of argument suggests that the hornblende, instead of being synmigmatitic, *may be premigmatitic or early synmigmatitic and helps initiate the segregation process* (Fig. 4).

This is a completely new and perhaps challenging way to interpret the role of hornblende in a migmatization process. Certainly, this is not the only interpretation of the occurrence of hornblende in migmatitic leucosomes but it may be an alternative that petrologists should be aware of.

The effect of fluids

The question whether metamorphic processes always involve the presence of a fluid phase or not has been discussed for a long time. Recently, Etheridge *et al.* (1983) suggested that substantial amounts of aqueous fluids are involved in low- and medium-grade regional metamorphism. In contrast, Thompson (1983) pointed out that "there is actually little compelling evidence to suggest that the presence of aqueous fluids is

common during metamorphism of the middle and lower crust". One exception is discontinuous dehydration reactions where the production rate of free liquid exceeds the escape rate. If this is correct it is of utmost importance for all models of migmatite formation and more or less precludes the formation of large partial melts at reasonable temperatures. However, it is generally accepted that the fluid (water) released in dehydration processes, and the fluids in any fluid inclusions enhance diffusion, reaction and deformation rates. Mistler & Coble (1974) showed that the presence of 10-30 nm wide effective grain boundaries increases diffusion velocities in various ceramics. Experiments on bishophite deformed at homologous temperatures comparable to those of subsolidus migmatite formation have shown an increase in diffusion velocity under slightly wet conditions (Urai 1983). In order to obtain the same strain rate under dry conditions a tenfold increase was necessary in the differential stress. A similar behaviour for silicates is a reasonable assumption which seems to be corroborated by experiments (e.g. Griggs 1967). According to Walther & Orville (1982), the fluid released during devolatization will fracture the rock and escape upward. They also suggested that quartz segregations in pelitic rocks marked the site of fluid escape after devolatization.

Theoretical approach

Solutions to diffusion problems caused by concentration gradients based on Fick's first and second laws have been published for different boundary conditions. On an atomistic level the problem is reduced to one, where the probability for an ion to jump from one region to another is proportional to the jump frequency, the number of atoms (i.e. the

concentration) and the jump distance. This tends to even out any concentration gradients. If diffusion is driven by a chemical potential other than concentration, the problem becomes more complicated. The increased free energy in the high potential part of the field increases the jump frequency causing a net transport of ions or atoms down the gradient. However, the relation between the mean pressure gradient and the jump frequency is unknown. To obtain a macroscopic solution, either appropriate additions to Fick's laws can be made or nonequilibrium thermodynamics applied. The nonequilibrium thermodynamic approach was evaluated by Weare *et al.* (1976). Fisher (1977) applied it to the growth of segregations formed due to an overstepping of the stability of a certain metamorphic paragenesis. This model is based on a matrix of phenomenological coefficients that relates fluxes to stress. However, all cross co-efficients in this matrix are unknown. Since there is no direct analogue between Fisher's study and migmatite formation, the same simplifying assumptions made by Fisher should not be applied here.

Shewmon (1963) applied Fick's first law to diffusion in response to a chemical potential gradient that was not related to concentration and obtained;

$$J = - D \frac{c}{RT} \frac{\delta \mu}{\delta x} \qquad (1)$$

where J is the resulting flux, D the diffusion coefficient, c concentration, x distance, μ the chemical potential, R the gas constant and T the absolute temperature. The equation has been changed here from an atomistic (in Shewmon's work) to a mole level. The change of the chemical potential caused by a mean pressure gradient is given by

$$d\mu = V d\bar{\sigma} \qquad (2)$$

where V is mole volume. There is no information on the pressure gradient versus x. Assuming a relation

$$\bar{\sigma} = \bar{\sigma}_o - ax \qquad (3)$$

i.e. the mean pressure decreases linearly with x, equation (1) can be reduced to

$$J = D \frac{c}{RT} \cdot V \cdot a \qquad (4)$$

Diffusion coefficients for real rocks are not easily obtainable. Assuming grain boundary diffusion in slightly "wet environments" as the rate controlling process, tabulations like that of Freer (1981) are of limited value. They only give minima for the coefficients. A conservative estimate for K^+-diffusion (lattice diffusion) from Freer's tabulation suggests $D = 10^{-19}\ m^2s^{-1}$ as a reasonable minimum value. Brady (1979) made experiments on nonporous "wet rocks" and estimated a maximum value for the diffusion coefficient to be $10^{-13}m^2s^{-1}$. In a later paper, theoretical considerations lead Brady (1983) to suggest a maximum value for the diffusion coefficient in similar environments to be less than $10^{-13} \cdot \delta/\alpha\ m^2s^{-1}$ where δ is the grain diameter and α the width of the intergranular region. For rocks with an average grain diameter greater than 0.1 mm, Brady (1983) proposed $10^{-11}\ m^2s^{-1}$ as a maximum diffusion coefficient. In the following text we use the smaller of these values ($10^{-13}\ m^2s^{-1}$) as an estimate. It is possible that diffusion coefficients in stressed rocks are close to this value. Assuming a mean pressure difference of 0.01 % of the confining pressure (rounded off to 5 kbar) i.e. 0.5 bar to occur over a linear distance of 2 cm suggests $2.5 \cdot 10^6 Nm^{-3}$ as a reasonable estimate for a in equation (3). An initial concentration of 3 % by weight of potassium oxide (c approximately $8.6\ 10^2$ mole m^{-3})

gives at 875K a flux between 3.2 10^{-18} mole $m^{-2}s^{-1}$ and 3.2 10^{-12} mole $m^{-2}s^{-1}$. From this flux it is possible to estimate the time needed for diffusion of material necessary to give the half width of an 8 cm wide leucosome consisting of 30 % microcline. The necessary time (t) would be an improbable 10^{12} years for the case of lattice diffusion. However, grain boundary diffusion would suggest a lower limit of only 10^{6} years.

The relation $x^2 \simeq D.t$ makes it possible to estimate diffusion distances. Allowing migmatites to form over a time period of 10^{6} years results in a diffusion distance of 1.8 m when the diffusion coefficient of Brady (1979) is applied. The above approach suggests that reasonable leucosomes widths are very unlikely to form by lattice diffusion. Thus, allowing for the approximations in the equations and the uncertainties in the applied values, it seems reasonable to propose that grain boundary diffusion in slightly wet rocks could produce the segregations found as leucosomes in migmatites.

Diffusion coefficients vary with the diffusing species. Tabulations of lattice diffusion coefficients (e.g. Freer 1981) show very large differences. There are no corresponding tabulations for grain boundary diffusion coefficients and the actual variations in the magnitude of diffusion coefficients are virtually unknown. It is logical to assume that corresponding differences exist, and this is corroborated by the field evidence already discussed. Diffusion velocities will also vary with fluid supply, grain boundary widths and stress patterns creating microfissures which act as diffusion avenues. The shear stress component is probably of great significance. It lowers the kinetic reaction resistance, enhances diffusion and if so facilitates the development and growth of segregation veins.

Mineral compositions

The same mineral species usually have similar compositions irrespective of whether they occur in the leuco-, meso- or melanosome. For members of solid solution series this poses the possibilities: (1) similar diffusivities for all the participating ions (cf. Brady 1983), (2) one specific ion controlling the rate, or (3) such minerals are inherited minerals and were never dissolved, transported and redeposited. The close similarity between the zoning of plagioclase in the leucosome and the mesosome suggests a choice between these possibilities. The zoning is most easily interpreted as a growth feature. This suggests that either much of the plagioclase has remained more or less stationary and that only minor amounts have been redeposited in the leucosomes, or, that there has been an important redeposition of phases also within the mesosomes. Keeping within the frames of traditional interpretations of the melanosome being a restitic "basic behind", it follows that some of the plagioclase is supplied to the leucosomes. The preservation of the zoning points to the minor importance of lattice diffusion in comparison with grain boundary diffusion.

Dynamic recrystallization

Migmatites sometimes show signs of recrystallization, e.g. irregular and/or wavy grain boundaries (grain boundary migration), subgrains etc. (Figs. 5a, b). These observations were often interpreted as due to post-deformative static recrystallization before the concept of dynamic recrystallization was recognized. It is here suggested that a possible synsegregational dynamic recrystallization can be followed directly by a static recrystallization at decreasing stresses (stress-drop annealing) in order to lower the strain energy of the rock.

a

b

Fig. 5. Microscopic pictures of leucosomes showing the very irregular grain boundaries of many grains, especially quartz (a-b), and the concentration of small grains along the grain boundaries (b). Legend: blank = quartz, cross-hatched = microcline, vertically ruled = plagioclase, horizontally ruled = hornblende, dotted = biotite, black = accessories.

In the present context it must, however, be admitted that it is probably very difficult to distinguish a synsegregationl dynamic recrystallization from a recrystallization that is connected to a later deformation event.

CONCLUSIONS

We conclude that under sufficiently high temperatures (575-675°C), a rock composed of minerals with different mechanical strengths, may start to segregate in a stress field. Small heterogeneities of this type are ubiquitous in all rocks irrespective of origin. The segregation process, once started, is self-perpetuating. The original heterogeneities are successively enlarged and continue to grow until either the temperature drops below a critical undefined value, the stress field decreases or mechanical equilibrium is reached. Robin (1979) suggested that the formation of melanosomes might lead to mechanical equilibrium. Minor metasomatic addition or minor anatectic melting may enhance the segregation but is not a requisite for solid state diffusion (aided by an intergranular fluid) to work.

ACKNOWLEDGEMENTS

We want to express our sincere thanks to Professor C.J. Talbot for interesting discussions and for critically reading the manuscript. We are also indebted to Professors W. Johannes and R. Gorbatschev and Drs. A. Wikström and T. Lundqvist for comments and M. Wikström and E. Hansson for typing the manuscript. The authors alone are responsible for the ideas and interpretations put forward in the paper. The work has been partially financed by the Swedish Natural Science Research Council.

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